

1                    METHOD AND APPARATUS FOR PARALLEL READOUT AND  
2                    CORRELATION OF DATA ON OPTICAL DISKS

3                    Background of the Invention

4                    **Field of the Invention**

5                    The present invention relates generally to a method and  
6                    apparatus for simultaneous parallel readout and correlation of  
7                    data on an optical disk and, more particularly, to a method  
8                    and apparatus for addressing or illuminating multiple disk  
9                    tracks and bits within each track containing data on the  
10                   optical disk with a light beam encoded with external data, and  
11                   for summing a light beam reflected from the disk, which  
12                   reflected light beam represents the product of the external  
13                   data and disk data.

14                   **Description of the Related Art**

15                   Optical disk memory is coming into very widespread usage.  
16                   The advantages include large storage capacity, compatibility  
17                   with existing memory access systems, and a remote or  
18                   non-contact sensing head. Data is stored as digital bits ("1"  
19                   or "0"), using mechanisms such as thermal ablation, phase

1 change, and reversal of a domain in a magneto-optic medium.  
2 Applications include commercial audio and video, databases,  
3 and computer memory. Developments now allow such optical  
4 disks to be either read-only (information pre-stored), write-  
5 once and read many times (WORM type), and erasable/rewritable.

6 An important additional advantage of optical disk memory  
7 over a magnetic disk is the potential for optical readout of  
8 many channels of information in parallel. Present readouts  
9 are single channel and position the optical readout beam using  
10 mechanical-type mechanisms used in magnetic disk memory  
11 devices. The access time is slower and readout time is no  
12 faster than for corresponding magnetic media; these are  
13 commonly perceived disadvantages of optical disks.

14 Massively parallel optical readout could overcome these  
15 disadvantages. However, two obstacles present themselves.  
16 The first problem is that the rate of data readout would be  
17 increased by a factor equal to the number of parallel readout  
18 channels; this effective rate would presumably be a large  
19 multiple of the single-head readout rate (typically 25  
20 Mbits/sec), which can cause data-rate overload (or mismatch)  
21 by the receiving device (e.g., the input to a computer or  
22 signal processing device) unless some measures are taken.

1           The second problem is that data encoding schemes and data  
2           formats for optical disks do not allow easy large-scale  
3           parallel readout using a single large-area optical beam. If  
4           multiple read heads are used, there is a practical limit on  
5           the order of ten channels, as well as a need to synchronize  
6           the multiple read heads. Therefore, there would be little  
7           advantage over a similar magnetic disk system. One scheme for  
8           overcoming this second problem is to store analog data on the  
9           optical disk using area modulation of a data cell with many  
10          binary bits to represent gray scale values. The disadvantage  
11          is loss of information capacity on a fixed-size optical disk.  
12          Moreover, this approach does not address the first problem of  
13          data-rate mismatch.

14                           Summary of the Invention

15          An object of the present invention is to perform a  
16          parallel optical readout of data from an optical disk without  
17          causing data-rate overload by the receiving device.

18          Another object of the present invention is the parallel  
19          readout of data stored on an optical disk using a single large  
20          area optical beam.

21          Another object of the present invention is to provide a  
22          system of correlating many channels of stored data with input  
23          data rapidly and accurately.

1           A further object of the present invention is the parallel  
2 readout of analog data stored on an optical disk using a  
3 radial beam.

4           The present invention involves rapidly searching data  
5 stored on an optical disk using optical readout to compare the  
6 stored data against external data encoded in a light beam  
7 projected onto the optical disk. The data stored on the  
8 optical disk and the external data may be vector arrays.  
9 Multiple bits of data are read out at the same time by a beam  
10 which illuminates plural tracks and plural bits within each  
11 track. The multiplicity of data bits read out in parallel  
12 from the optical disk are simultaneously compared (correlated)  
13 with the external data. Data is encoded onto the optical  
14 disk, preferably in the conventional binary form. The  
15 comparison or correlation operation is performed utilizing  
16 convolution. The present invention can be particularly  
17 utilized for pattern matching.

18           The above-mentioned and other objects and features of the  
19 present invention will become more apparent from the following  
20 description when read in conjunction with the accompanying  
21 drawings. However, the drawings and descriptions are merely  
22 illustrative in nature and not restrictive.

Brief Description of the Drawings

Fig. 1 is a diagram illustrating a first embodiment of the present invention having an encoded light beam projected onto an optical disk for parallel readout of data;

Fig. 2 is a plan view of an optical disk onto which a light beam encoded with data is projected in the present invention;

Fig. 3 is a diagram of four time slices showing the overlap of the projected light beam on the optical disk in the present invention;

Fig. 4 is a diagram of the CCD array involved in the reception and analysis of the reflected light beam;

Fig. 4A is a truth table useful in understanding the circuit diagram of Fig. 5;

Fig. 5 is a diagram illustrating the switching mechanism for transmitting data to the appropriate CCD accumulator/shift register;

Fig. 6 is a diagram illustrating a second embodiment of the present invention having an encoded radial sign light beam projected onto an optical disk for parallel readout of sign bits and having an encoded trapezoidal data light beam projected onto the optical disk for parallel readout of data;

Fig. 7 is a diagram of two time slices showing the

1 projected radial sign light beam on the optical disk and the  
2 projected data light beam on the optical disk in the second  
3 embodiment of the present invention.

4 Fig. 8 is a diagram illustrating a third embodiment of  
5 the present invention having an encoded light beam projected  
6 onto an optical disk for parallel readout of data;

7 Fig. 9 is a graph illustrating phase encoding in the  
8 third embodiment; and

9 Fig. 10 is a diagram of a conventional quadrature  
10 detection circuit.

11 Description of the Preferred Embodiments

12 The present invention involves a pattern matching scheme,  
13 which correlates external data with data stored on an optical  
14 disk. Preferably, the data is stored on the optical disk as  
15 digital data; however, the data may also be stored as analog  
16 data. If the data is to be stored as digital data, the  
17 negative data can be converted to a two's compliment format  
18 before storing the data on the optical disk. However, it is  
19 preferable to store the data as digital data in its original  
20 format on the optical disk.

21 The pattern matching scheme of the present invention has  
22 many applications. For example, the digital data stored on

1 the optical disk may represent models such as the modes or  
2 paths of sound waves travelling through water under a  
3 particular set of conditions. The set of conditions may  
4 include water temperature and salinity. The disk data may  
5 represent the vector components of a plurality of models of  
6 paths or modes. Preferably, each model for a path or mode is  
7 stored on a separate track. The external data may represent  
8 the vector components of an actual sound wave travelling  
9 through the water, which was sensed by a hydrophone or other  
10 sensing device. The external data is correlated with each  
11 model stored on the optical disk to determine which model most  
12 closely corresponds to the actual sensed external data. Such  
13 pattern matching allows the path of an incoming sound to be  
14 determined and the source of the sound to be located.

15 The pattern matching scheme of the present invention is  
16 not limited to correlation of sound waves with models of paths  
17 or modes. The external data may represent any pattern to be  
18 correlated with a plurality of sets of data representing  
19 patterns stored on an optical disk.

20 The pattern matching scheme preferably employs  
21 convolution to perform the actual correlation of the external  
22 data simultaneously with a set of models stored, preferably

1     digitally, on an optical disk to determine which model most  
2     closely corresponds to the external data.

3             Before discussing the details of the present invention it  
4     is important to understand the fundamentals associated with  
5     data correlation. The product of two binary numbers,  $x = (\alpha_1,$   
6      $\alpha_2, \dots \alpha_n)$  and  $y = (\beta_1, \beta_2 \dots \beta_n)$ , can be generated by a  
7     convolution of the numbers, with the order of the significant  
8     bits of one of the numbers reversed. The product is a  
9     weighted sum of the convolution terms, given by the following  
10    expression:

$$\sum_{j=1}^{k=1,2,\dots,n} 2^{2n-(k+1)} \alpha_j \beta_{k+1-j} + \sum_{j=k}^n 2^{2n-k} \alpha_j \beta_{k+n-j} \dots (1)$$

11    Where the total number of terms is  $2n-1$ , the significance of  
12    the bits decreases with increasing subscript on  $\alpha$  and  $\beta$ , i.e.,  
13    subscript = 1 labels the most significant bit and subscript =  
14     $n$  labels the least significant bit, and the weighting  
15    coefficients are the powers of "2", which are determined by  
16    the number of tracks  $m$  and the number of bits in a set of data  
17     $n$  stored in each track when the data is provided on tracks.

18             The conventional binary multiplication involved in  
19    convolution is cumbersome to perform. The data optically read  
20    is converted into electrical signals, which are multiplied  
21    using an electronic multiplier. This leads to severe



1 limitations on the number of channels addressable in parallel.  
2 Thus, it is advantageous to generate analog results of  
3 convolution optically by using a method called digital  
4 multiplication by analog convolution (DMAC). Implementation  
5 of a DMAC algorithm for matrix multiplication has been  
6 previously reported (Ravindra A. Athale, Huy Q. Hoang and John  
7 N. Lee, "High Accuracy Matrix Multiplication with Magneto-optic  
8 Spatial Light Modulator", Soc. Photo-Inst. Eng., Vol. 431,  
9 pages 187-193(1983) incorporated by reference herein). The  
10 result of performing a DMAC operation is an analog number  
11 obtained by evaluating the power series sum of equation (1).  
12 If the binary numbers x and y are corresponding components of  
13 two vectors, X and Y, the analog product of Equation (1) is  
14 one component of the inner product of the vectors. The inner  
15 product of two complex vectors  
16  $X = X^R + iX^I$  and  $Y = Y^R + iY^I$  is

$$\begin{aligned} X^\dagger Y &= \sum_j X_j^* Y_j = \sum_j (X_j^R Y_j^R + X_j^I Y_j^I) + i \sum_j (X_j^R Y_j^I - X_j^I Y_j^R) \\ &= Z^R + iZ^I, \end{aligned} \quad \dots (2)$$

19 where the dagger ( $\dagger$ ) signifies transpose and complex  
20 conjugation, the asterisk denotes inner-product

1 multiplication, the subscript  $j$  labels the components in  
2 vector space, and  $R$  and  $I$  label the real and imaginary parts  
3 of  $X$  and  $Y$  respectively. Here the output of an inner product  
4 operation results in two quantities,  $Z^R$  and  $Z^I$ , regardless of  
5 the number of vector components.

6 Fig. 1 shows a first embodiment of the present invention  
7 which utilizes DMAC. A laser (light) beam 8 generated by a  
8 laser 10 is focused by a lens (not shown) and passed through a  
9 conventional weighting or optical modulator 20 which is driven  
10 by a modulator driver 9 that produces a bit data stream that  
11 modulates the intensity of the beam in accordance with  $2^p$   
12 where  $p=0,1,\dots,(2n-2)$ . For example, if  $n=8$  bits,  $p=0,1,\dots,14$   
13 and the modulation weights equal  $2^0, 2^1, 2^2, \dots, 2^{14}$ . The  
14 modulated beam 22 passes through at least one conventional  
15 focusing lens 30 and is applied to a second conventional  
16 modulator called a spatial modulator 40. An example of the  
17 conventional spatial modulator 40 is a Bragg cell. The  
18 spatial modulator 40 modulates the beam 22 according to input  
19 external data ( $Y$ -input), thereby producing a weight and input  
20 data modulated beam 42. The output of the spatial modulator  
21 40 passes through at least one conventional lens 50 that  
22 spreads the beam into a trapezoidal shape. The trapezoidal

1 shaped beam illuminates plural tracks and plural bits on each  
2 track of a rotating optical disk 60 (see Fig. 2).

3 The reflection of the trapezoidal beam from the optical  
4 disk 60, called a reflected beam 62, is the inner product of  
5 the input data and the data stored in the tracks ( $x*y$ , for  
6 each of  $m$  tracks). The reflected beam 62 is focused by at  
7 least one conventional lens 70 onto a receiving linear  
8 detector array such as a CCD array or photodetector array 81  
9 (Fig. 4) contained in a receiving device 80. The  
10 photodetector array 81 has at least one light sensor, such as  
11 a photodetector, for each of the  $m$  tracks of data. The lens  
12 70 essentially converts the reflected trapezoidal beam into a  
13 line beam or one dimensional beam that illuminates the  
14 detectors of the linear array. When the trapezoidal beam is  
15 reflected off the optical disk 60, the reflected beam 62 is  
16 the result of multiplying (the inner product) all of the data  
17 in each track by both the weighted bit data stream controlling  
18 the intensity of the trapezoidal beam and the input external  
19 data controlling the spatial modulation of the trapezoidal  
20 beam.

21 The inner products are accumulated by the photodetector  
22 array 81 (Fig. 4) and can be transmitted from the receiving  
23 device 80 to a computing device 90, such as a conventional

1 computer, by way of a conventional current measuring device  
2 88, to determine which of the tracks has the data having the  
3 highest correlation with the input external data.

4 An alternative method of performing the analog conversion  
5 operation without the conventional weighing modulator 20 is to  
6 apply the weighing coefficients of the convolution terms in  
7 Equation (1) at the photodetector array 81 (Fig. 4) with  
8 electronic amplifiers. This approach has the advantage of  
9 reducing problems of non-linearity and limited dynamic range  
10 of the modulator 20.

11 Fig. 2 shows the weight and spatially modulated beam  
12 illuminating a trapezoidal area on the optical disk 60. The  
13 optical disk 60 has  $m$  tracks, which are illuminated by the  
14 beam. In addition,  $n$  bits on each of the  $m$  tracks are  
15 illuminated as shown in Fig. 2.

16 The photodetector array 81 (Fig. 4) has  $m$  photodetectors.  
17 Each of the  $m$  photodetectors of the photodetector array 81  
18 (Fig. 4) corresponds to a track and essentially receives the  
19 part of the reflected beam that is the product of the weighted  
20 input external data and the  $n$  bits on the corresponding track,  
21 which are illuminated by the trapezoidal beam. Eventually the  
22 data on each of the  $m$  tracks is read out as it rotates into  
23 and out of the trapezoidal beam as multiplied by the

1 externally provided input data. This performs the  
2 multiplications of equation (1). A more detailed description  
3 of this will be described with respect to Fig. 3.

4 Fig. 3 is an example of the convolution of one of the  $m$   
5 tracks with the trapezoidal beam, actually with the portion of  
6 the trapezoidal beam illuminating that track. Fig. 3 shows  
7 the convolution of a set of data  $x$  ( $x = x_1, x_2, x_3 \dots x_n$ )  
8 stored on an optical disk 60 in a track with a second set of  
9 input external data  $y$  ( $y = y_1, y_2, y_3 \dots y_n$ ) modulated onto a  
10 beam and illuminating  $n$  bits of the optical disk 60 in the  
11 track. In this example,  $n=8$ . The set of data  $x_1, x_2, x_3 \dots x_n$   
12 may be referred to as the disk bits. The input external data  
13  $y_1, y_2, y_3 \dots y_n$  may be referred to as the weighted input data  
14 bits. Each of the two sets of data,  $x$  and  $y$ , are associated  
15 with a sign bit  $S_x$  and  $S_y$ , respectively. The total number of  
16 terms for the convolution is  $2n-1$  or in this example 15.  
17 However, the set of data  $x$  is merely one of the  $m$  tracks on  
18 the disk and the same operation is happening with respect to  
19 other tracks illuminated by the trapezoidal beam. That is,  
20 the trapezoidal beam having encoded the second set of input  
21 external data  $y$  is involved in the convolution of not only the  
22 set of data  $x$  on the one track shown in Fig. 3, but also in  
23 the convolution of each set of data stored on each of the  $m$

1 tracks simultaneously. Fig. 3 shows the convolution of the  
2 two 8-bit sets of data,  $x$  and  $y$ , at intervals from sign  
3 determination to the end of the convolution.

4 At time interval A the start bit, "1", and sign bit  $S_y$  of  
5 the input external data are multiplied by the sign bit  $S_x$  of  
6 the set of data on the track of the disk and the start bit  
7 "1", respectively during the reflection. The sign bit thus  
8 read out is used to route the output data as will be discussed  
9 in more detail later. At the time interval B, the weighted  
10 input data bits  $y_2, y_3$  and  $y_4$  are multiplied by zero, the disk  
11 bits  $x_2, x_3, x_4$  and  $x_5$  are multiplied by zero and the disk bit  
12  $x_1$  is multiplied by weighted input data bit  $y_1$ . That is, the  
13 corresponding photodetector for this track receives a  
14 reflected beam at the time interval B which is essentially  
15  $x_1 * y_1$ . At time interval C, the weighted input data bits  $y_1, y_2,$   
16  $y_3 \dots y_8$  are multiplied by the disk bits  $x_8, x_7, x_6, \dots x_1,$   
17 respectively. That is, the corresponding photodetector for  
18 this track receives a reflected beam at the time interval C  
19 which is essentially  $y_1 * x_8, y_2 * x_7 \dots y_8 * x_1$ . This is the midpoint  
20 of the convolution. At the time interval D, the weighted  
21 input data bits  $y_5, y_6, y_7$  and  $y_8$  are multiplied by zero and the  
22 disk bits  $x_8, x_7, x_6$  and  $x_5$  are multiplied by zero. That is,

1 time interval D represents the end of convolution. The total  
2 number of terms in this example is  $2(8)-1=15$ .

3 Synchronization of the rotation of the optical disk and  
4 the modulation of beam may be achieved by using a clock from a  
5 master clock generator 95 (Fig.1). For example, a pulse of  
6 light lasting 40 nanoseconds could be used to read the sign  
7 bits. The light beam may then be turned off until  
8 approximately 20 nanoseconds before the most significant bits  
9 of x and y are at their midpoint of convolution. Thereafter,  
10 it may be switched at the rate of 25 megahertz as it steps  
11 through the weighing coefficients of equation (1). In this  
12 example, the bandwidth of the spatial modulator should be at  
13 least 50 megahertz, corresponding to a rise time of less than  
14 20 nanoseconds. This will produce a beam that reaches its  
15 power peak at each weighing step when the stream of bits in  
16 the light beam is aligned with all of the bits in the set of  
17 data on the disk, since the bits convolve at a rate of once  
18 every 40 nanoseconds.

19 The signal detected by the photodetector array 81 (Fig.  
20 4) while the bits are misaligned will result in some smearing  
21 of the convolution products, and it may be necessary to  
22 overcome this by separating the bits by zeros, which will  
23 reduce by one-half the number of operations that can be stored

1 on disk as well as reduce the processing rate. An alternative  
2 is to electronically switch the detectors on for a time much  
3 less than 20 nanoseconds near the midpoint of each weighing  
4 step to prevent the smearing of convolution products as they  
5 are received.

6 Figure 4 shows the receiving device 80, comprised of the  
7 photodetector array 81 connected to a switch array 100,  
8 accumulator/shift registers 85A and 85B connected to the array  
9 100, and an amplifier 120 connected to the accumulator/shift  
10 registers 85A and 85B. The truth table of Figure 4A shows the  
11 possible output for each of the  $m$  switching circuits of switch  
12 array 100 and routs signs to either the positive CCD  
13 accumulator/shift register 85B or the negative CCD  
14 accumulator/shift register 85A. When the sign bits,  $S_x$  and  $S_y$ ,  
15 are read out in the photodetector array 81, for example, the  
16 photodetector corresponding to the track storing the set of  
17 data  $x$  and the sign bit  $S_x$  provides a current based on the  
18 analog sum to a corresponding switching circuit in the switch  
19 array 100, which responds by selecting the negative CCD  
20 accumulator/shift register 85A or the positive CCD  
21 accumulator/shift register 85B depending upon the analog sum  
22 of the sign bits. As convolution terms of  $x$  and  $y$ , for  
23 example, are received by the corresponding photodetector of



1 photodetector array 80, the photodetectors generate a current  
2 based upon each convolution term. This current is transmitted  
3 to the negative or positive CCD accumulator/shift register  
4 (85A-85B) depending upon switch selection. The selected CCD  
5 accumulator/shift register accumulates and stores the charge  
6 from the currents representing the convolution terms.

7 For example, if both  $S_x$  and  $S_y$  equal zero, the analog sum  
8 equals zero and the switch of the switch array 100,  
9 corresponding to the photodetector receiving the products of  
10  $x * y$ , selects the positive CCD accumulator/shift register to  
11 store and accumulate the convolution terms. If  $S_x$  equals zero  
12 and  $S_y$  equals one, the analog sum equals one and the switch  
13 selects the negative CCD accumulation/shift register 85A to  
14 store and accumulate the convolution terms. If  $S_x$  equals one  
15 and  $S_y$  equals zero, the analog sum equals one and the switch  
16 selects the negative CCD accumulator/shift register 85A to  
17 store and accumulate the convolution terms. If both  $S_x$  and  $S_y$   
18 equal one, the analog sum equals two and the switch selects  
19 the positive CCD accumulator/shift register 85A to store and  
20 accumulate the convolution terms. This is shown in the truth  
21 table in Fig. 4A.

22 The clocked-synchronized switch driver 110 drives the  
23 corresponding switch of the switch array 100 providing a path

1 for the current from the corresponding photodetector of the  
2 photodetector array 80 to the corresponding accumulator/shift  
3 register (85A or 85B) as the convolution terms are received by  
4 the photodetector of the corresponding photodetector array 81.

5 When the convolution is completed, the accumulated  
6 charges are transmitted serially to an amplifier 120. If a  
7 particular accumulated charge is from the negative CCD  
8 accumulated/shift register 85A, the charge is transmitted to  
9 the inverting input of the amplifier 120 and if the charge is  
10 from the positive CCD accumulated/shift register 85B, the  
11 charge is transmitted to the noninverting input of the  
12 amplifier 120.

13 Although this example involved only one set of data x  
14 associated with a sign bit stored on one track, this operation  
15 applies to each set of data on each track. That is, the data  
16 from adjacent tracks can be switched to different registers.

17 The detection and accumulation of the convolution terms  
18 of one set of data with its associated sign bit on each track  
19 multiplied by the input external data with its associated sign  
20 bit occurs simultaneously and in the same manner as the above  
21 example. The sets of data associated with the track producing  
22 the greatest accumulation of charge in the CCD

1 accumulator/shift registers 85A-85B, according to Equation  
2 (2), has the highest correlation with the input external data.

3 Figure 5 shows the switching circuit for processing the  
4 sign signals for one photodetector element in the  
5 photodetector array 81. There is a signal processing circuit  
6 for each track. A photodetector 95 of the photodetector array  
7 81, corresponding to the reflected beam encoded with the  
8 convolution terms of  $x*y$ , detects the analog sum of the sign  
9 bits as well as the convolution terms. The clocked-  
10 synchronized switch driver 110 is synchronized with the laser  
11 and rotation of the optical disk. When the analog sum of the  
12 sign bits  $S_x$  and  $S_y$  are detected, the clocked-synchronized  
13 switch driver 110 causes switching device 130 to connect the  
14 photodetector 95 to a sign bit determination circuit 135.  
15 When the photodetector is to detect the convolution terms, the  
16 clocked-synchronized switch driver 110 causes the switching  
17 device 130 to connect the convolution terms to a switch 105 of  
18 the switch array 100. The analog sum of the sign bits are  
19 received by a threshold comparator 140 and a NAND gate 160.  
20 One of the inputs of the NAND gate 160 is held at "1". If the  
21 analog sum is "0", the NAND gate 160 outputs "1" to an  
22 amplifier 170. If the analog sum is "1" or "2", the NAND gate  
23 160 outputs a "0" to the amplifier 170.

1           If the threshold comparator 140 receives an analog sum of  
2           2, the threshold comparator outputs a "1" to an AND gate 150.  
3           If the threshold comparator receives a "0" or a "1", the  
4           threshold comparator outputs "0".

5           The AND gate 150 has one input which is held at "1".  
6           If the AND gate 150 receives a "1", the AND gate 150 outputs a  
7           "1" to the amplifier 170. If the AND gate 150 receives a "0"  
8           from the threshold comparator 140, the AND gate 150 outputs a  
9           "0" to the amplifier 170.

10          The amplifier 170 amplifies the resulting signals, and  
11          outputs the information to the clocked switch driver 125. The  
12          clocked switch driver 125 drives the switch 105 to connect the  
13          photodetector 95 to the negative CCD accumulator/shift  
14          register 85A register or the positive CCD accumulator/shift  
15          register 85B depending on whether the resulting signal is a  
16          binary "1" or a binary "0", respectively.

17          In this example, it was assumed that the one set of data  
18          and a sign bit  $S_x$  represented a number on a track. However,  
19          each of the tracks can have several sets of data with  
20          corresponding sign bits representing one model. The sign bits  
21          and convolution terms are read out in parallel  
22          (simultaneously). Each track has a corresponding  
23          photodetector to detect the reflection beam indicating the

1 analog sum of the sign bits or the convolution terms of the  
2 sets of data representing the model stored in each track. The  
3 convolution terms are then stored and accumulated in a  
4 corresponding location of the CCD accumulator/shift register  
5 arrays (85A-85B).

6 Each model can be represented by a vector. For example,  
7 the model can be represented by a vector  $X$  in which one of the  
8 components is the set of data  $x$  having a corresponding sign  
9 bit  $S_x$ . Several sets of data, each having a corresponding  
10 sign bit, could represent vector components of vector  $X$  on the  
11 track. Each track would have several sets of data with a  
12 corresponding sign bits to represent a plurality of vectors  
13 representing a plurality of models. In this example, the  
14 input external data is a vector  $Y$  in which one of the  
15 components is  $y$  having a corresponding sign bit  $S_y$ . Each  
16 vector component of the input external vector  $Y$  would be  
17 multiplied by the corresponding vector component in each of  
18 the tracks simultaneously to produce the analog products of  
19 the vector components using the same apparatus and method as  
20 described in the previous example to implement Equation (1).  
21 The sum of the analog products produced by multiplication of  
22 vector components of the vectors  $X$  and  $Y$  represents the  
23 product of two vectors as in Equation (2). In the present

1     example, each vector stored in each track is multiplied by  
2     input external vector Y to produce vector products.  
3     Concurrent serial readout of the CCD accumulator/shift  
4     register 85A-85B of the CCD array occurs after all of the  
5     inner products are calculated and accumulated in the shift  
6     register so that Equation (2) is implemented. The vector  
7     stored on the track on the disk which produces the highest  
8     current when multiplied with the input external vector, has  
9     the highest correlation with the input external vector.

10         Fig. 6 shows a second embodiment of the present  
11     invention, which has the advantage of improved utilization of  
12     the storage density capability of the optical disk 60.

13         The weight and modulated input beam is generated in the  
14     same manner as in the first embodiment of the present  
15     invention. However, the weight and input data modulated beam  
16     does not have a sign bit. A separate modulated sign beam,  
17     which is modulated based on the sign bit of the external data,  
18     is used to read out the sign bit of each set of data on each  
19     of the m tracks. The sign beam in this case is essentially a  
20     radial beam or one dimensional beam rather than a two  
21     dimensional trapezoidal beam.

22         The sign beam encoded with the sign bit is preferably  
23     offset by a small angle from the optic axis of the weight and

1 input data modulated beam. The optic axis of the sign beam is  
2 brought into coincidence with that of the weight and input  
3 data modulated beam by a beam splitter 180. The sign beam is  
4 directed onto a sign photodetector 82 located near the end of  
5 the photodetector array 81. The transmission of the beam  
6 splitter 180 can be chosen higher than its reflection to  
7 conserve signal beam power, since the power available in the  
8 laser may be a limiting constraint; a higher power diode laser  
9 can be used to replace the sign beam power lost at the beam  
10 splitter 180. A more detailed description of the operation of  
11 the second embodiment will be described with respect to Fig.  
12 7.

13 Fig. 7 is an example of the convolution of one of the m  
14 tracks with the two beams shown in Fig. 6. The components of  
15 vector X are stored as sets of data on one of m tracks. Each  
16 set of data has a corresponding sign bit. The components of  
17 vector Y are encoded onto the weight and input data modulated  
18 beam, which is a trapezoidal beam. As in the first  
19 embodiment, the trapezoidal beam having the encoded input  
20 external data, is involved not only in the convolution of the  
21 plurality of sets of data on the one track shown in Fig. 7,  
22 but also in the convolution of each of the sets of data stored  
23 on each of the m tracks.

1       The synchronization of the rotation of the optical disk  
2       and the two beams is achieved by using clocks from master  
3       clock generator 95 to perform the reading out of the sign bits  
4       and the convolution of the components.

5       Fig. 7 shows two time intervals, A and B. At time  
6       interval A, the sign beam is turned ON and the weight and  
7       modulated input beam is turned OFF. The sign beam reads out  
8       the analog sum of the sign bits such as  $S_x$  and  $S_y$ . The start  
9       bit, "1" and the sign bit  $S_y$  of the input data are multiplied  
10      by the sign bit of the disk data  $S_x$  on the track of the disk  
11      and the start bit "1", respectively.

12      At the time interval B, the sign beam is turned OFF and  
13      the weight and modulated input beam is turned ON. At time  
14      interval B, the corresponding photodetector for this track  
15      receives a reflected beam and produces a current based on the  
16      reflection beam. As the disk rotates, all of the convolution  
17      terms of all of the components of the vector of the track  
18      shown in Fig. 7 are read out and summed to produce currents,  
19      which are accumulated and stored in the same manner as  
20      described in the first embodiment. The vector components on  
21      each track are simultaneously multiplied and summed in the  
22      same manner as described in the present example. As in the  
23      first embodiment, the vector components stored on the track,



1     which produce the highest current when multiplied by the input  
2     external vector, has the highest correlation with the input  
3     external vector.

4             In the first two embodiments of Figs. 1 and 6, the models  
5     (data representing the signal being compared) have been stored  
6     circumferentially. However, the data can be stored on an  
7     optical disk with the predominant dimension across-track or  
8     radially as in the third embodiment discussed below. The  
9     optical disk can also be divided into groups of tracks,  
10    wherein each group of tracks is called a supertrack and  
11    contains data representing one model. Preferably there are  
12    512 tracks in a supertrack. In such a situation, data is  
13    stored both radially and circumferentially. Each supertrack  
14    has radial stripes, which cross all the tracks in the  
15    supertrack. Each stripe is formed by a bit on each track of  
16    the supertrack. If there are 512 tracks in a supertrack, for  
17    example, the length of the radial stripe is 512 bits. A gray  
18    scale data representation may be obtained by changing the bit  
19    configuration of a radial stripe. The rate at which the  
20    models are read out decreases relative to the first two  
21    embodiments. The fastest readout rate of the third embodiment  
22    occurs when each model is distributed along one supertrack.

1 Each model again may represent a vector. The amplitude and  
2 phase of each vector may be encoded in separate supertracks.

3 Figure 8 shows a third embodiment of the present  
4 invention reading out models or patterns, such as  $A_{70}$ , stored  
5 in a radial direction on super tracks of an optical disk 200.  
6 The model may be a complex vector  $X$ . A laser beam generator  
7 205 generates a laser beam 210, which is focussed by lens 220  
8 to produce a focused laser beam 230. A spatial modulator 235,  
9 such as a Bragg cell, receives the beam 230 as well as input  
10 external data, such as a complex vector  $Y$  representing a  
11 pattern or model. The spatial modulator 235 modulates the  
12 beam 230 based on the input external data to produce an input  
13 modulated beam 238 or point beam. The point beam 238 is  
14 spread into the radial beam 250 by a lens 240 and onto the  
15 optical disk 200 to simultaneously illuminate at least one  
16 radial stripe, such as radial stripe 252, on all of the  
17 supertracks. However, several radial stripes are usually  
18 illuminated as shown in Figure 8. The reflection of the  
19 radial beam 250 from the disk, called a reflected beam 255  
20 carries the data products (convolution terms) of the input  
21 external data and the data stored on each supertrack of the  
22 optical disk 220. The reflected beam 255 is received by a  
23 detection array, such as photodetector array 260, which

1 generates currents for the super track based on the data  
2 products encoded in the reflection beam 255. The current is  
3 output continuously from each element of the photodetector  
4 array 260 to quadrature detection circuits 270, which separate  
5 the AC component from the DC component of the currents and  
6 then separate the AC components into real and imaginary  
7 components for each supertrack. The quadrature detection  
8 circuits 270 are well known circuits.

9 The real and imaginary components of the currents are  
10 continuously transmitted to a measuring device 280 to  
11 determine a value for each the currents produced by the data  
12 products encoded in the reflection beam 255. These values are  
13 then transmitted to a computing device 290 which determines  
14 which of the supertracks has the highest correlation with the  
15 external data.

16 A more detailed description of this will be described by  
17 way of example in reference to Figs. 8-10.

18 First, it is necessary to describe how the amplitude and  
19 phase of the complex vector  $X$  is stored on a supertrack, such  
20 as  $A_{70}$ , of rotating optical disk 200 as disk data. The complex  
21 vector  $Y$  represents an input external data modulated radial  
22 beam 250. When the beam 250 encoded with the vector  $Y$   
23 traverses the disk data in the super track  $A_{70}$  on a rotating

1 optical disk 200, the disk data are treated as a signal on a  
2 carrier having an amplitude and phase. In this manner complex  
3 numbers can be encoded on the optical disk 200, such as the  
4 vector  $X$ , which represents for example an 8-bit complex  
5 number. The complex vector  $X$  on a carrier of radian frequency  
6  $\omega$  (frequency of rotation of the optical disk 200) has a vector  
7 component  $X \exp(i\omega t)$ , where  $X = x \exp(i\theta)$ ,

$$x = \sqrt{(X^R)^2 + (X^I)^2}, \quad \theta = \tan^{-1}(X^I/X^R).$$

9 Encoded on the disk is  $A$  as disk data, which is the real part  
10 of the signal in supertrack  $A_{70}$ :

$$\begin{aligned} 11 \quad A &= x \cos(\omega t + \theta) \\ 12 \quad &= 1/2[X \exp(i\omega t) - X^* \exp(-i\omega t)]. \quad \dots (3) \end{aligned}$$

13 A pseudocarrier frequency is related to the bit rate  $f_b$  of the  
14 rate of rotation of the optical disk by

$$15 \quad \omega/2\pi f_b = 1/M, \quad \dots (4)$$

16 where  $M$  is the number of samples of  $A$  encoded on the disk per  
17  $2\pi$  rad. The phase and the amplitude of  $A$  are encoded on the  
18 disk by writing radial stripes, such as radial stripe 252, of  
19 length (in bits) given by Eq. (3) to the nearest whole number  
20 in super track  $A_{70}$ .

21 Figure 9 shows two plots of the real part  $A$ , of a complex  
22 signal, on two cycles of a carrier signal. The effective

1 carrier frequency,  $f$ , is, for example,  $f_p/4$ . Equivalently,  
2 the carrier period equals four sampling intervals. The phase  
3 shift  $\theta$  in Fig. 9(b) is achieved by changes in the amplitude  
4 of  $A$  at the sampling points as given by the expression for  $A$   
5 with  $\theta \neq 0$ . The numerical quantity written on the disk is the  
6 whole number of bits closest to the value of  $A$ . With no phase  
7 shift, the samples of  $A$  consist of radial stripes of bits,  
8 such as radial stripe 252, distributed as follows (for 8-bit  
9 digital resolution): at  $t = 0$ , 512 bits; at  $t = \Delta t$ , 256 bits;  
10 at  $t = 2\Delta t$ , 0 bits; at  $t = 3\Delta t$ , 256 bits; at  $t = 4\Delta t$ , 512  
11 bits, etc. When  $A$  is shifted by a phase angle  $\theta$ , the numbers  
12 of bits in each stripe are the whole numbers of bits closest  
13 to  $256 \cos(2\pi f n \Delta t + \theta) + 256$ , with  $n = 0, 1, 2, 3, 4$ . These  
14 plots indicate that a change in phase will cause a change in  
15 amplitude and vice versa because the samples are always taken  
16 at the same time during the rotation of optical disk 200.

17 Second, it is necessary to discuss how the amplitude and  
18 phase of the external data, for example complex vector  $Y$ , is  
19 encoded by the laser 205. The laser 205 is modulated acousto-  
20 optically or electro-optically by  $B$ , the real part of a vector  
21  $Y$  having a  $y$  component on a carrier  $\omega$ ,  $B$  will have the same  
22 form as  $A$ :

23 
$$B = y \cos(\omega t + \phi) \quad . . . (5a)$$

1                                 $= 1/2[Y \exp(i\omega t) + Y^* \exp(-i\omega t)] \quad . . . (5b)$

2        where  $y$  and  $\phi$  ( $\phi = \tan^{-1} (Y^I/Y^R)$ ) correspond to  $x$  and  $\theta$  in Eq.  
3        (3). The external vector  $Y$  must be well synchronized with a  
4        disk rotation that is known to be slightly irregular. The  
5        rotation speed of optical disk 200 should be tied to the  
6        modulator signal rate of spatial modulator 235 by a drive  
7        signal to correct for the irregularity. The drive signal to  
8        the modulator could be delayed after its rate is sampled to  
9        provide time for changing the rotation speed of optical disk  
10       200. Another method synchronizes the modulator signal rate to  
11       the optical disk. This can be accomplished by a person of  
12       skill in the art with synchronization pulses read from the  
13       optical disk. As indicated by Figure 9 and discussed above,  
14       this synchronization is important because a change in phase  
15       results in a change in amplitude.

16                Moreover, the phase of  $Y$  is placed on the carrier, as  
17        shown explicitly in Eq. (5a). Whereas data on the disk is  
18        area modulated, data on the light beam is power modulated.  
19        The length of  $B$  at the disk is preferably 512 tracks for a  
20        bipolar 8-bit correlator. A modulator, such as the Bragg cell  
21        previously mentioned, may be chosen with a bandwidth much  
22        higher than  $\omega$  to effect the modulation.

1           The inner product of the vector components of vectors  $X$   
2   and  $Y$  encoded in the reflection beam 255 is

3    $AB = 1/4[XY\exp(i2\omega t) + X^* Y^* \exp(-2i\omega t) + XY^* + X^*Y]. \quad \dots (6)$

4   We let  $XY = Z$  and note that the object of the calculation is  
5   to obtain  $Z^R$  and  $Z^I$ , the real and the imaginary parts of  $Z$ ,  
6   respectively.  $Z^R$  and  $Z^I$  in Eq. (7) below may be extracted from  
7    $Z$  by one of the quadrature detection circuits 220. A  
8   conventional quadrature detection circuit is shown in Fig. 10.  
9   The AC coupler in the circuit (or a high-pass filter that cuts  
10   off below the baseband signal frequency) removes the two DC  
11   terms in Eq. (6). Equation (6) then becomes (after dropping  
12   the two DC terms that do not yield results of interest),

13            $AB = (1/4)[Z^R\sin(2\omega t) - Z^I\sin(2\omega t)]. \quad \dots (7)$

$$\text{where } Z = \sqrt{Z^R^2 + Z^I^2}, \quad \psi = \theta + \phi$$

14           After the real and imaginary parts are extracted by the  
15   corresponding one of the quadrature detection circuits, the  
16   measuring circuit 280 measures the values of the data products  
17   and transmits these values to the computing device 290. The

1     computing device determines which of the super tracks contains  
2     the patterns or models having the highest correlation with the  
3     input external data.

4             The advantages and capabilities of the present invention  
5     are discussed in more detail in "Highly Parallel Architecture  
6     for Optical Disk Database Correlation with Compensation for  
7     Database Errors", Applied Optics, Vol. 31, No. 14, May 10,  
8     1992 by the inventors hereof and incorporated by reference  
9     herein.

10            While the invention has been illustrated and described in  
11     detail in the drawings and foregoing description, it will be  
12     recognized that many changes and modifications will occur to  
13     those skilled in the art. It is therefore intended, by the  
14     appended claims, to cover any such changes and modifications  
15     as fall within the true spirit and scope of the invention.